International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

Space applications: monolithic diffraction grating elements from EUV to NIR spectral range

Alexandre Gatto

Alexander Pesch

Lars H. Erdmann

Matthias Burkhardt

et al.

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 1056315 · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304153

SPACE APPLICATIONS - MONOLITHIC DIFFRACTION GRATING ELEMENTS FROM EUV TO NIR SPECTRAL RANGE

Alexandre Gatto[1], Alexander Pesch[1], Lars H. Erdmann[1], Matthias Burkhardt[1], Alexander Kalies[1], Torsten Diehl[2], Peter Triebel[2], Tobias Moeller[2]
[1] Carl Zeiss Jena GmbH (Germany). [2] Carl Zeiss Microscopy GmbH (Germany)

ABSTRACT

Monolithic diffraction gratings are one of the key components of high sensitive spectral imaging systems including spectrometer used in space instruments. These gratings are optimized for high efficiency, lowest line spacing errors and low scattering values to improve the performance of a spectral imaging system. Spectral imaging systems lead to enhanced remote sensing properties when the sensing system provides sufficient spectral resolution to identify materials from its spectral reflectance signature comprising low signal-to-noise ratios.

Keywords: passive optical components, diffractive optics, grating, custom design grating, aberration-corrected grating, free-form or toroidal grating, monolithic grism, holography, gray-scale lithography, ion etching, remote sensing application

1. INTRODUCTION

Beside binary and sinusoidal gratings - blazed type gratings are in general the best choice for achieving maximum diffraction efficiency and low polarization sensitivity in a moderate spectral range. Over recent years, Zeiss has established a systematic manufacturing process to produce monolithic, real blazed gratings (transmission or reflection), based on a combination of holographic recording and ion beam etching together with in-house processing of high-end grating substrates. Blazed type gratings provide a tunable spectral response curve even for imaging gratings by mixing the characteristics of different grating angles, variable line spacing and variable profile depths without influencing the spectral resolution of the space instrument. This paper presents the manufacturing process of real blazed monolithic gratings on flat surfaces (including grisms) and curved surfaces such as spherical, aspherical or free-form shapes.

2. DESIGN APPROACH OF MONOLITHIC GRATINGS

In this paper we will show the results of considering the complete design steps of an optical diffraction grating starting with the numerical modeling of the grating parameter (groove density, groove depth and grating profile) with respect to diffraction efficiency as well as polarization sensitivity.

The method used Rigorous Coupled Wave Analysis (RCWA) [1] that is acknowledged as well suited technique to simulate spectra or diffraction responses. The approximation of simulated efficiencies and polarization properties will be aligned with already manufactured grating profiles to achieve high conformity between theoretical simulation and manufactured profiles while analyzing their efficiency and polarization sensitivity (See Fig. 1).

Fig. 1.a. is showing the phase profile of a grating as initial setup for the RCWA analysis and resulting field distribution calculated by RCWA. Using an ideal blazed grating profile (Fig. 1. b.) the discretization of the profile will be done using a variable grid approximation.
The efficiency calculation of gratings for space applications is based on using real produced profiles (Fig. 1.c). These grating profiles are measured with AFM in order to precisely calculate the spectral responses. The discretization with variable grid allow for very high conformity with the real measured profile. In order to the polarization sensitivity an iterative process starting with a real profile and further profile optimizations towards the required polarization sensitivity are also part of the design analysis. Recent designs of later on manufactured gratings show polarization sensitivities smaller than 0,05 using the following equation[2]:

$$P = \frac{T_{TE} - T_{TM}}{T_{TE} + T_{TM}} \tag{1}$$

The result of the optical design analysis will be used as a parameter for further Ray Tracing simulations.

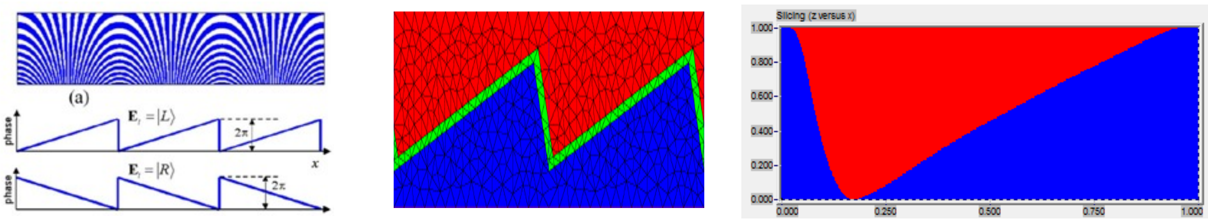

Fig 1.: a. Phase profile of a grating as initial setup for the RCWA analysis and the resulting field distribution b. Ideal blazed grating profile with variable grid discretization c. Produced grating profile measured with AFM. Figures b. and c. blue denotes the substrate material (Fused Silica is widely used)

In the next step Ray Tracing based simulations are used to optimize the holographic recording setup with its individual optical elements and their positions. The design of the exposure optics is adapted to achieve highest imaging quality with respect to blaze profile, line straightness and groove density variation (see Fig. 2).
Ray Tracing simulations can also be used to optimize the imaging performance within the spectral range and help to correct wavefront errors, aberrations, astigmatism and chromatic aberration in order to enhance spectral resolution of the sensing instrument.

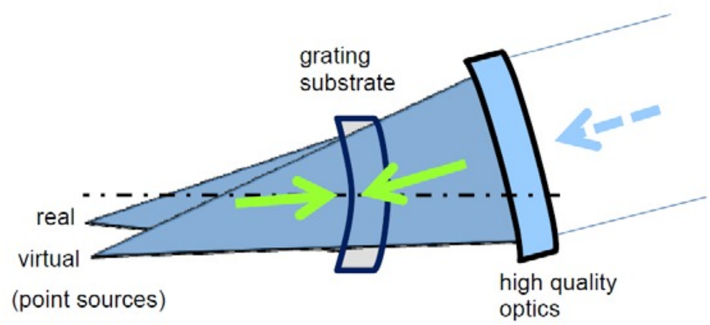

Fig 2.: Scheme of a double side exposure setup using a transparent substrate for recording real blazed profiles into photoresist

Due to certain degree of freedom for realizing holographic recording set-up gratings on prism substrates can also recorded with a very high accuracy without any bonding or cementing process during the manufacture of the element.

3. MANUFACTURING APPROACH OF MONOLITHIC, HOLOGRAPHIC GRATINGS

For many years ZEISS has been manufacturing monolithic diffraction gratings for applications in the EUV, UV, VIS and NIR. Commonly, monolithic gratings are gratings that are etched into transparent material, mostly Fused Silica, and contain no organic residues or resists. Holographic gratings can be produced on plane and curved (convex, concave or free-form shape) substrates [3-13].
Different spectrometer setups (e.g. Flat-Field, Offner, etc.) require plane or convex / concave shaped grating substrates with high precision optical surfaces. Such surfaces can be produced with lowest wavefront error

down to λ/20 (rms). Latest laser interferometer metrology ensures exact surface form accuracy (radius, irregularity) measurements.
In order to reduce high order aberrations, aspherical and free-form surfaces can be alternatively processed (see Fig. 3.) to allow more degrees of freedom in the optical design of spectroscopic instruments with less optical elements and therefore size and weight advantages. Surface form accuracy can be tested with interferometer and Computer Generated Hologram (CGH). A CGH can be made for testing aspheres and free form optics almost as simple as testing of rotationally symmetric optics. Using a CGH allow a Null-Test of the manufactured surface compared to the nominal surface profile. Surface form measurements of recently manufactured free-forms (toroid) show wavefront errors of rmsa better than 0.1 lambda. Slope errors, resulting from midspatial frequency errors caused by sub-aperture surface polish, can be measured down to 0.1 arcsec rms (depending on the actual geometry). This precision can be used for the substrates for the holographic recording.
Precision polished optical surfaces allow low distorting optical imaging. Besides the optical imaging properties, straylight significantly influences the overall instrument performance [13]. The goal of any grating manufacturing process is to reduce straylight to a minimum level. ZEISS has implemented advanced optical polishing techniques to be able to produce optical surfaces with micro-roughness finish of better than 0.3nm rms based on substrate level.
Various substrates material like Fused Silica, optical glass or CaF2 can be chosen for the holographic recording process as long as there are light transmitting to certain extend.

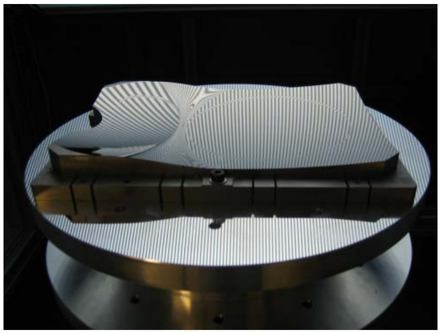

Fig 3.: Sample of produced free-from optical element with complex offset

After the manufacture of the grating substrate, the substrate is coated with a photo sensitive material (photoresist). The photoresist is exposed by positioning the coated grating substrate between the interfering, monochromatic, coherent beams of light from a laser (holographic setup). Many spectrometer applications require high efficiency gratings with a precisely defined grating structure over the full aperture of the optical active area. Fig. 2. shows schematically a recording setup that is based on a bi-directional recording of a real blazed intensity pattern into the photoresist layer. The especially designed interference patterns within the resist layer enable a gradually blaze-like exposure of the resist-layer.

The complete grating recording process starts with the laser exposure to enable the recording of a real blazed grating intensity pattern into the photoresist material (see Fig. 2.). Since the photoresist is soluble, the blazed intensity pattern becomes a blazed surface pattern after being immersed in solvent (wet-chemical etching). The development of the exposed resist-layer and following ion beam etching is shown in Fig. 4..

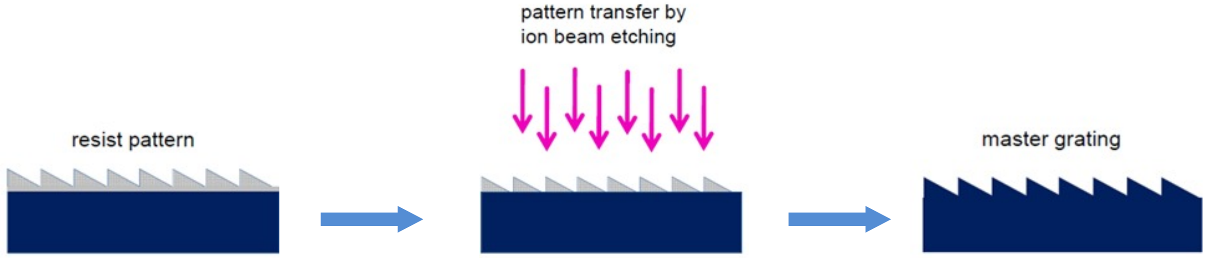

Fig. 4.: The grating manufacturing process starting with the a real blazed profile resist-layer and following ion beam etching ending up with a monolithic microstructure.

The ZEISS unique technology of manufacturing real-blazed profiles comprising transparent substrates is well suited for the production of transmission gratings. Many years of expertise in the research and development of optical coatings [14-15] enable high transmission anti-reflection coatings from the DUV to the NIR. ZEISS has developed specially adapted coating processes (Ion beam sputtering, ion-assisted deposition and so on) for maintaining the micro-structure of blazed gratings in particular [13]. Besides of transmission gratings, numerous spectrometer setups (e.g. Offner, Rowland circle, Czerny-Turner system layout) working on the optical design principles of reflection gratings. This technology steps can be applied to manufacture high quality reflection gratings from the EUV to the IR applications with an outstanding level of low stray light and ghost diffraction order by employing a combination of holography and reactive ion beam etching together with the in-house coating capabilities.
Recent developments refer to universal UV-VIS-NIR spectrometers with a single grating to cover the UV to NIR by an optimized diffraction efficiency. UVVIS and NIR spectrometer are capable to cover a detection wavelength range of 1000nm or even more. Due to wide wavelength ranges a constant depth of blaze over the grating area will cause a grating efficiency with a gradient to the UV or NIR as shown in Fig. 5 (dashed lines). By etching two zones with different depth into one resist grating will create an overall optimized diffraction efficiency Thus 50 percent of the optical active area shows a behavior like a UV-grating with a peak due to the application setup slightly above 300nm. The other grating area corresponds to a VIS/NIR-grating with a broader peak between wavelengths of 800nm and 1µm. Thus, this grating would provide an overall efficiency as indicated by the solid line that corresponds to the mean value of the two initial curves. It clearly shows a more balanced efficiency over the spectral region of interest (see Fig. 5.)

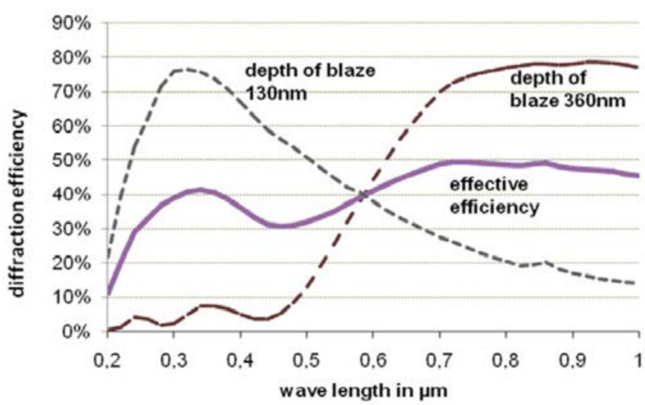

Fig. 5.: Spectral efficiencies (unpolarized) for the -1th diffraction order for two different depths of a holographic blazed type profile (dashed lines) and resulting efficiency curve for the imaging grating (solid line)

Besides having two zones of different depth for the blazing of the grating a (nearly) continuous change in depth can be realized. Fig. 6 shows an AFM image of a modulated blazed grating with remarkable very smooth depth variation without any discontinuity between adjacent grooves. In fact of that and the very smooth surface a very low stray light will occur.

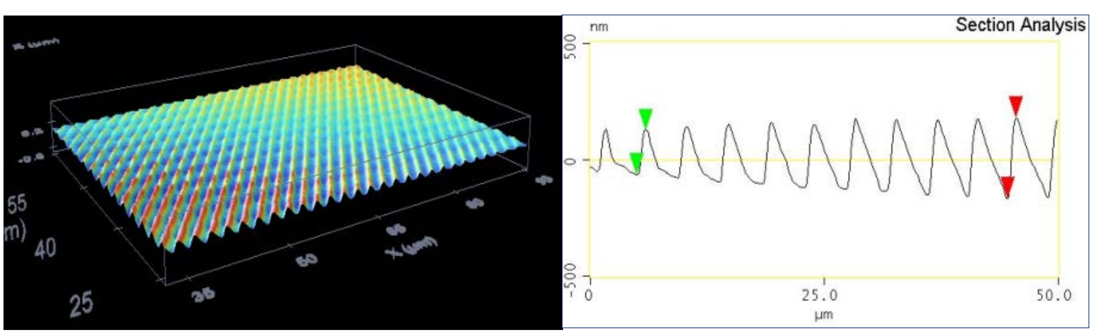

Fig. 6.: AFM measurement of the transition region between the two different blaze depths. At the right side a AFM scan between the middle of the transition range towards the deeper blazed region is shown.

4. EXPERIMENTAL RESULTS – EFFICIENCY AND STRAYLIGHT

Chapters 2 and 3 have shown the capabilities for designing and manufacturing of monolithic, real blazed gratings with different surface profile including free-form surfaces. In the following chapter two examples of high efficiency gratings will be described in detail.
As first example an already manufactured and characterized EUV grating for the wavelength range 5nm and 25nm is shown. This grating has a line density of 1200l/mm and a blaze angle of 3.6° optimized for the first diffraction order. The grating is Ruthenium coated maintaining the microstructure. In Fig. 7 the measured efficiencies are shown [16]. Different grating samples (red, blue, gray) are analyzed in order to optimize the optical coating.

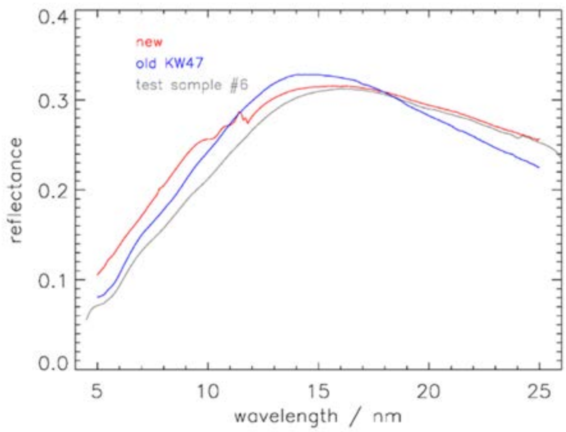

Fig. 7.: Efficiency measurements in the wavelength range between 5nm and 25nm for a blaze angle between of 3.6° [16]. Different grating samples (red, blue, gray) are analyzed in order to optimize the optical coating.

The second example is a high efficiency grating with blazed profile. The groove density is 1200l/mm, optimized for the UVVIS wavelength range [13]. Enhanced efficiency of the grating itself combined with low scattered light in the angular distribution enable high optical resolution spectrometer instruments. Focusing on the straylight characteristic a measurement of the actual straylight level, preferably with extremely high precision, was performed. In Fig. 8. a measured BRDF of the grating is shown.

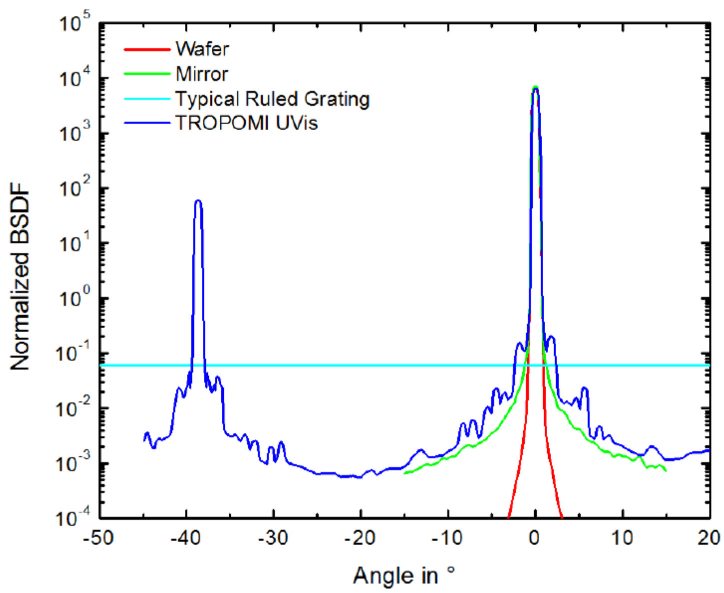

Fig. 8.: Existing measurement results, straylight measurement BRDF of a blazed grating 1200l/mm within the TROPOMI project [13]

The suppression of the ghost level of 10^{-4} is verified with this measurement.

5. CONCLUSION

Spectral imaging systems lead to enhanced sensing properties when the sensing system provides sufficient spectral resolution to identify materials from its spectral reflectance signature. The performance of diffraction gratings provide an initial way to improve instrumental resolution. Thus, subsequent manufacturing techniques of high quality gratings are essential to significantly improve the spectral performance.
ZEISS has developed advanced manufacturing techniques to produce monolithic, high groove density gratings with low stray light, high diffraction efficiency and low polarization sensitivity characteristic. Gratings at ZEISS are produced holographically in combination with ion beam plasma etching to enhance the grating profile. Typical profile shapes are real blazed type gratings allowing to optimize efficiency and polarization requirements exactly towards the required spectral range from EUV to NIR. Holographic gratings (transmission or reflection type) can be produced as plane and curved elements (convex, concave or free-form shape) with outstanding quality of in-house produced substrates and coatings.

REFERENCES

[1] Integral equation method with parametrization of grating profile theory and experiments
BH Kleemann, A Mitreiter, F Wyrowski, Journal of Modern Optics 43 (7), 1323-1349 54 1996
[2] Polarization Holography, L. Nikolova, P. S. Ramanujam, Cambridge University Press, 2009
[3] http://www.zeiss.de/gratings
[4] http://www.zeiss.de/spectral

[5] Alexandre Gatto, "Microstructured optics for high performance optical systems", Proceedings of SPIE Vol. 8613, 86130U (2013)
[6] Oliver Sandfuchs, Matthias Burkhardt, Reinhard Steiner, Alexandre Gatto, Robert Brunner, " Holographically microstructured gratings for high-performance spectrometers", DGaO Proceedings 2011, http://www.dgaoproceedings. de, ISSN: 1614-8436, 0287-2011-B027-2
[7] Jacqueline Maass, Oliver Sandfuchs, Alexandre Gatto, et al., "Talbot-carpets of periodic and quasi-periodic close-packed 2D mask structures calculated by a modified chirp-z-algorithm", Proceedings of SPIE Vol. 8428, 84281L (2012)
[8] Oliver Sandfuchs, Alexander Pesch, Robert Brunner, "Rigorous modeling of dielectric and metallic blaze gratings in the intermediate structure regime", SPIE Proceedings Vol. 6675 (2007)
[9] O. Sandfuchs, et al., Modelling adapted to manufacturing aspects of holographic grating structures, Journal of the European Optical Society - Rapid Publications 6, 11006 (2011)
[10] R. Brunner et. al."Diffractive refractive hybrid microscope objective for 193 nm inspection systems", Proc. SPIE 5177, 9–15 (2003).
[11] R. Brunner, et al., "New solutions to realize complex optical systems by a combination of diffractive and refractive optical components", Proc. SPIE 5183, 47–55 (2003).
[12] M. Burkhardt et al., "Functional integrated optical elements for beam shaping with coherence crambling property, realized by interference lithography" Appl. Optics 46, 7061–7067, (2007).

[13] Reinhard Steiner, Alexander Pesch, Lars H. Erdmann, Matthias Burkhardt; Alexandre Gatto, Robert Wipf, Torsten Diehl, H. J. P. Vink, B. G. van den Bosch "Fabrication of low stray light holographic gratings for space applications", Proc. of SPIE Vol. 8870 (2013)
[14] Martin Bischoff, Maik Sode, Dieter Gäbler, et al., "Metal fluoride coatings prepared by ion-assisted deposition" (Conference Proceedings), Proc. SPIE 7101, Advances in Optical Thin Films III, 71010L
[15] Winfried Arens, Detlev Ristau, Jens Ullmann, et al., "Properties of fluoride DUV excimer laser optics: influence of the number of dielectric layers" (Conference Proceedings), Proc. SPIE 3902, Laser-Induced Damage in Optical Materials
[16] M. Burkhardt et al., "Streulichtarme holografische Blaze-Gitter für den EUV-Bereich", DGaO Proceedings 2014, http://www.dgao-proceedings.de, ISSN: 1614-8436, urn:nbn:de:0287-2014-P019-1